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THE RATE OF PROPAGATION OF ULTRASONIC WAVES IN HUNGARIAN ROCKS, AND ITS CORRELATION WITH OTHER PHYSICAL AND CHEMICAL ROCK CHARACTERISTICS

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THE RATE OF PROPAGATION OF ULTRASONIC WAVES IN HUNGARIAN ROCKS, AND ITS CORRELATION WITH OTHER PHYSICAL AND CHEMICAL ROCK CHARACTERISTICS

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ABSTRACT: An ultrasonic laboratory method for establishing the rate at which elastic waves are propagated in a number of carbonaceous rocks (mainly limestones), as well as in some siliceous rocks, is discussed. The relationship between velocity and physical and chemical characteristics of those rocks is explained. Further research is required in order to explain the principles underlying the difference between results obtained in the laboratory and those obtained under field conditions.

Fundamental Measurement Principles

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We made our measurements with an ultrasonic instrument. The essence of the measurement method is the determination of the resonance frequency in a rock section of known thickness by means of oscillations of known frequency. The rate of propagation of the oscillation can be calculated from the resonant frequency and the section thickness. This can be done in practice by placing /86 the rock section on a quartz crystal which is then excited by an oscillator. The oscillations of the quartz crystal penetrate continuously into the rock specimen and are reflected from its opposite surface. By changing the frequency of the quartz crystal with the oscillator, we can reach the point where the frequency entering the rock section, and the natural frequency of the rock specimen are in resonance. Resonance is indicated by a sudden increase in energy, which can be observed on a microammeter, or acoustically, or perhaps simultaneously, using both methods.

The base frequency, that is, the minimum frequency at which this resonance will appear is proportional to the rate of propagation of audio oscillations in the specimen, and is inversely proportional to the double thickness of the specimen.

Resonance also appears at the upper harmonics of the base frequency. The base frequency can, therefore, be determined from the differences in the frequency

* Numbers in the margin indicate pagination in the foreign text.

values of the resonant peaks of the upper harmonics that follow each other.

On the basis of the foregoing the numerical value of the velocity

$$V = 2d.\delta f$$

where d is the rock section thickness, δf is the frequency difference between adjacent resonant frequencies.

No corrections were incorporated in the velocity calculation. Measurements made using aluminum test specimens measuring 30 x 29, 6 x 45, 30 x29, 8 x 59, and 30 x 29 and 7 x 100 mm showed that deviations of the scope indicated geometric dimensions cause no more than a 2% change in velocity. The nature of the findings was such that this can be ignored. The dimensions of the specimens used for the measurements did not differ from each other to the extent cited.

Practical Measurements

Measurements were made using specimens cut from the rock. The specimens were made up into sections with two parallel planes. Where rock stratification was obvious in the rock sample, the section was cut parallel with this stratification. Section thickness generally varied between 6 and 12 mm; area was approximately 40 x 40 mm. The sides of the samples were not finished, that is, they had an irregular fracture. The cut specimens were ground because contact between quartz crystal and specimen surfaces has an effect on the amount of energy that penetrates the specimen. Smoothness of the polished surface is necessary for reflection of energy. Energy is scattered when reflected from a rough surface, so resonance cannot develop. Contact between crystal and specimen is improved by a thin layer of vaseline.

Measurements were made in the 0.65 to 2.0 MHz range. This corresponds to a wave length between 0.009 and 0.003 m at a velocity of 6000 m/s. The diameter of the surface of the excited quartz crystal used for the measurements was 35 mm, so specimen size was of this order of magnitude. Resonance was observed simultaneously with a milliammeter and acoustically. Specimen thickness was measured with calipers accurate to within 1/20 mm.

Sources of Errors in Measurement /87

The results of the measurements are influenced by the degree of contact between the specimen and the crystal, the material used for the contact, the thickness of the crystal, and the difference between the exciting frequency and the natural frequency of the crystal. Efforts were made to keep the first two factors constant by grinding specimen surfaces to the same smoothness, and by always using vaseline. The same crystal was used for all measurements, and all measurements were made in the same frequency range, so these can be ignored as sources of error because the systematic error they cause is within the limits of accuracy for informative type measurements.

Most errors were found to result from non-parallelism of the rock surfaces, by inaccuracy in measuring thickness, and by inaccuracy in reading the resonance peaks.

Non-parallelism of surfaces used for measurements on the one hand hampers the development of resonance (and above a certain limit makes measurement impossible), and on the other makes the thickness measurement less certain.

Accurate reading of the frequencies of resonant peaks is made difficult by the flat, indistinct nature of the peaks. The definiteness of resonance is also influenced by the smoothness of the specimen's reflecting surface, lack of homogeneity in the surface of discontinuity within the sample, and by individual rock characteristics.

The SiO_2 content was in excess of 9% in 20 rock specimens. In the majority of these, in 14 specimens, no resonant peak could be observed. The reason for this may be that the SiO_2 disturbs the homogeneity of limestones, and thus, depending how it is distributed, and its amount, disturbs, or even hinders, the development of resonance. This is also proved by the fact that the mean SiO_2 content for all specimens measured was 17%, and the SiO_2 content in those specimens that did yield velocity values is only 6%. Sandstones are an extreme case, in that their granular structure results in resonance being observed in them in only exceptional cases. In fact, this also happened only when the physical difference between binding material and grain is small (sandstone cemented with silicic acid).

The mean measurement error for 25 specimens was arrived at by making several velocity determinations (Figure 1). The mean error was 227 m/s. This is permissible in measurements of this type.

Table 1 lists deviations in individual measurements of thickness and frequencies as they pertain to individual resonant peaks, as well as resulting velocities. This table also lists the effect of deviations in individual measurements as they change the final result. According to the table, the error in thickness is 0.2 mm maximum, but generally does not exceed 0.1 mm.

The results of measurements made using 9.8 mm and 19.4 mm thick sections taken from No. 40 Upper Triassic dolomitic limestone, the first listing in the table, are similar within the margin of error, and these, together with the measurements made using the aluminum standards mentioned, demonstrate that specimen thickness has no effect on the final results.

TABLE 1. DEVIATIONS AS A RESULT OF SEVERAL MEASUREMENTS /89

Specimen No.	d_1 mm	d_2 mm	d_1-d_2	f_1	f_2	f_1-f_2	V_1	V_2	ΔV
40	9,8	19,4	9,6	0,308	0,155		6050	6000	50
46	8,5	8,3	0,2	0,35	0,34	0,01	5950	5650	300
59	7,9	7,9	0,0	0,38	0,39	0,01	6000	6170	170
107	9,4	9,4	0,0	0,32	0,30	0,02	6020	5650	370
111	9,1	9,0	0,1	0,34	0,34	0,00	6200	6120	80
120	9,3	9,2	0,1	0,25	0,30	0,05	4660	5520	860
121	8,8	8,8	0,0	0,35	0,34	0,01	6160	5990	170
162	6,9	6,9	0,0	0,39	0,40	0,01	5380	5520	140
163	10,6	10,7	0,1	0,30	0,31	0,00	6350	6650	300
175	9,5	9,5	0,0	0,31	0,30	0,01	5900	5700	200
176	11,3	11,4	0,1	0,28	0,265	0,205	5880	6050	170
178	8,7	8,7	0,0	0,31	0,31	0,00	5400	5400	0
179	6,4	6,5	0,1	0,42	0,43	0,01	5380	5600	220
195	8,6	8,5	0,1	0,36	0,36	0,00	6200	6120	80
196	10,5	10,5	0,0	0,30	0,30	0,00	6300	6300	0
197	10,5	10,5	0,0	0,30	0,29	0,01	6300	6100	200
198	11,9	12,0	0,1	0,25	0,25	0,00	5950	6000	50
199	8,0	8,1	0,1	0,37	0,35	0,02	6900	5670	230
201	6,1	6,1	0,0	0,45	0,47	0,02	5500	5740	240
202	8,2	8,1	0,1	0,37	0,33	0,04	6070	5350	720

Commas represent decimal points.

The procedure used was only approximately 50% useful in finding velocity values for the specimens prepared for measurement. In some samples it was the porosity, in others the SiO_2 content, that made it impossible to observe resonance, or if observed, only very weakly. Yet there were specimens the porosity and SiO_2 content of which were so slight that this could not be the reason

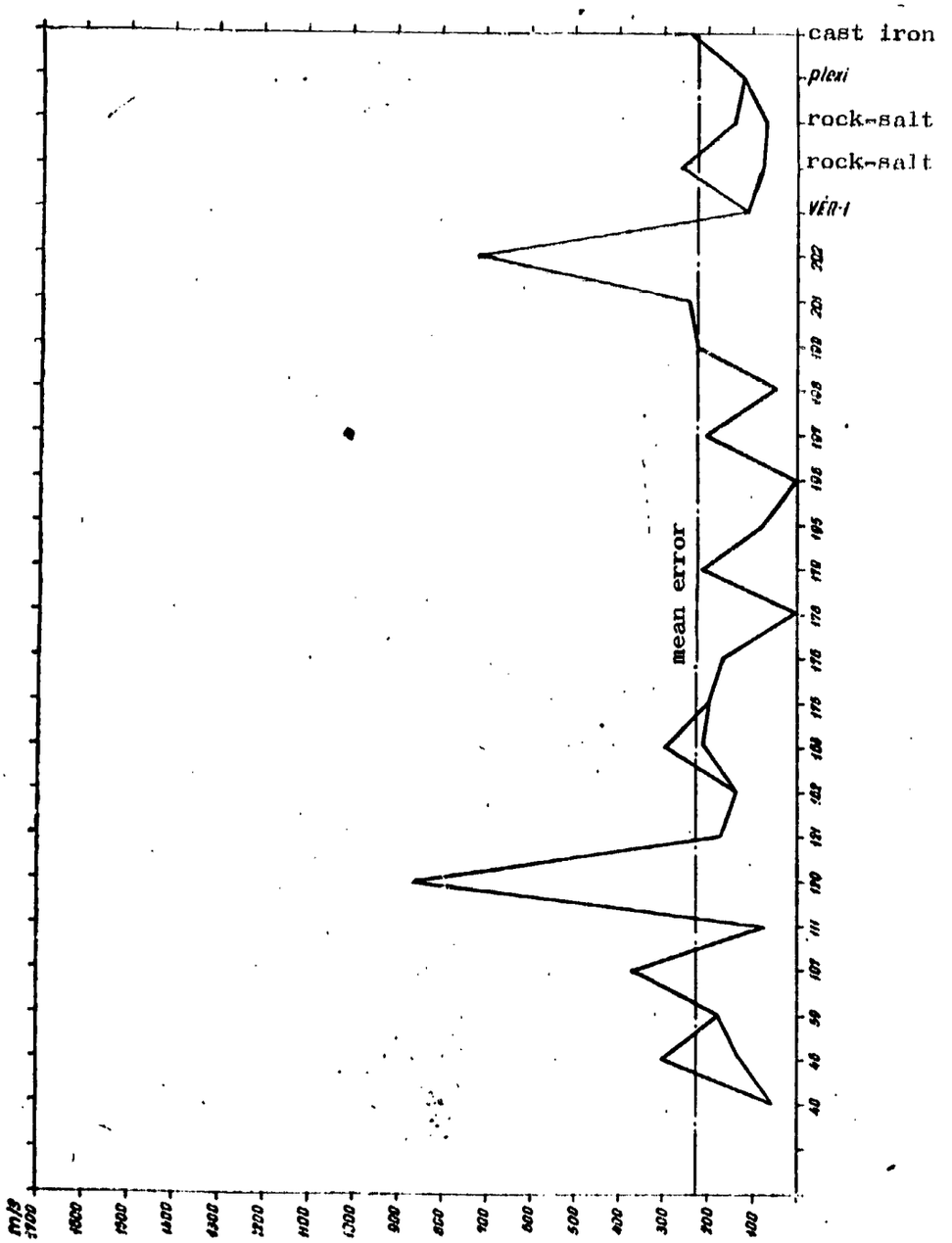

Figure 1. Standard Deviation in the Velocity Measurements.

for lack of resonance. In these cases, the measurement failure apparently can be explained by the error source already mentioned, or by some rock characteristic, but we cannot pinpoint it accurately.

Results

We were fortunate in receiving from the Hungarian State Geological Institute a group of specimens whose geological age, density, gravimetric density, porosity, and SiO_2 and CO_2 content were known (Table 2). (As is customary, chemically determined ingredients were stated in the oxide form so that SiO_2 actually means the total Si, and CO_2 the total inorganic C, that is, the carbonate content.) This made it possible to compare the velocity findings directly with other rock data. The group of specimens was collected from outcrops.

Methods of mathematical statistics were used to process results, we also tried to illustrate the correlation between the data obtained in various ways by experiment and comparison and to characterize them with numerical indices. This was necessary because the correlation was not always evident and statistical methods can be used to indicate the degree, and the quality, of correlations, graphically and numerically.

This goal is reached for the most part by making the calculations, or by /90
plotting the correlation coefficient, its square, linear regression, standard deviation, and, finally, the correlation curve.

The correlation coefficient was calculated through the formula

$$r = \frac{\Sigma xy}{n\sigma_x \sigma_y}$$

where x and y represent the deviations of the individual points from the arithmetic means, and n is the number of data. σ_x and σ_y are obtained using the following equations:

$$\sigma_x = \sqrt{\frac{(x - \bar{x})^2}{n}} \quad \text{and} \quad \sigma_y = \sqrt{\frac{(y - \bar{y})^2}{n}}$$

The linear regressions were calculated through $Y' = b(x - \bar{x}) + \bar{Y}$. The correlation of the two variables was made in terms of the regression of X in terms to Y, and with the regression of Y in terms of X, that is, in terms of two

TABLE 2.

Order No.	Rock	Age	Velocity	Density	Gravimetric Density %	Porosity	SiO_2	Co_2
19	Rock flour colomitic limestone	Liassic	5580	2.72	2.53	6.98	21.35	31.66
21	Clay rock limestone	Dogger	4060	2.80	2.52	10.00	12.25	33.67
33	Anhydrite	Lower Triassic	5530	2.89	2.81	2.42	2.65	50.75
35	Calcareous aleurite	Lower Triassic	5100	2.69	2.50	7.06	43.49	14.41
37	Dolomite	Middle Triassic	6460	2.69	2.54	5.50	0.20	46.92
40	Dolomitic limestone	Upper Triassic	6025	2.75	2.64	4.00	1.62	40.55
46	Closely packed limestone	Upper Triassic	5790	2.73	2.60	4.26	0.00	43.42
57	Closely packed limestone	Middle Triassic	5960	2.68	2.53	5.60	0.15	42.79
58	Dolomite	Middle Triassic	5800	2.84	2.65	6.30	0.13	46.60
59	Dolomitic limestone	Lower Triassic	6080	2.82	2.67	5.47	0.31	43.88
86	Closely packed limestone	Lower Cretaceous	5950	2.76	2.60	5.79	0.82	42.38
88	Closely packed fossiliferous limestone	Lower Cretaceous	4370	2.70	2.59	4.37	10.61	37.95
90	Closely packed limestone	Lower Cretaceous	4750	2.69	2.51	6.69	5.31	38.79
107	Closely packed limestone	Upper Triassic	6020	2.85	2.52	11.40	0.24	43.12
108	Closely packed limestone	Middle Triassic	5940	2.73	2.63	4.00	1.47	42.49
111	Brecciated limestone	Upper Triassic	6160	2.70	2.46	8.90	3.30	39.93
120	Closely packed limestone	Dogger	5090	2.70	2.48	8.60	1.59	41.78
121	Closely packed limestone	Dogger	6080	2.68	2.44	9.80	1.59	42.22
131	Rock flour flint	Middle Triassic	4420	2.59	2.40	7.00	81.68	5.51
161	Closely packed limestone	Middle Triassic	5800	2.90	2.81	3.10	5.59	38.74
162	Closely packed limestone	Middle Triassic	5450	2.63	2.54	3.80	0.32	42.61
163	Dolomite	Upper Triassic	6520	2.81	2.68	4.60	0.00	46.19
165	Closely packed limestone	Lower Triassic	4850	2.90	2.69	7.20	0.93	42.13
167	Porous dolomite	Lower Triassic	6100	2.78	2.58	7.10	0.80	45.24
169	Closely packed limestone	Lower Triassic	5040	2.59	2.50	7.30	4.10	39.62
175	Limestone with flint	Middle Triassic	5800	2.78	2.60	6.47	7.73	39.22
176	Closely packed limestone	Middle Triassic	5960	2.66	2.56	3.75	0.61	42.54
178	Sandy limestone	Lower Cretaceous	5400	2.80	2.64	5.71	19.27	33.26

TABLE 2. (Cond't)

Order No.	Rock	Age	Velocity	Density	Gravimetric Density %	Porosity	SiO_2	Co_2
179	Requienic limestone	Lower Cretaceous	5490	2.76	2.62	5.00	0.15	43.18
195	Closely packed limestone	Lower Cretaceous	6160	2.90	2.84	2.30	0.25	42.48
196	Closely packed limestone	Malm	6300	2.69	2.62	2.60	0.17	42.52
197	Closely packed limestone	Lower Cretaceous	6200	2.65	2.31	12.80	0.20	41.93
198	Closely packed limestone	Lower Cretaceous	6000	2.75	2.63	5.20	0.37	42.13
199	Closely packed limestone	Middle Triassic	5780	2.77	2.68	4.10	1.97	41.41
201	Closely packed limestone	Middle Triassic	5620	2.62	2.56	2.10	0.79	42.49
202	Closely packed limestone	Middle Triassic	5710	2.81	2.74	2.64	0.09	42.49

straight lines. The angle formed by the two straight lines also shows the degree /91 of correlation. If r = 1, the two regression lines coincide.

Of course, this characterization is more accurate and more reliable, the more data used. It is possible therefore that the results can change in time with the increase in the availability of data. Yet, as a first approximation the following may serve as good support for what follows.

We had already measured the velocity in 21 rocks of the Triassic, 7 rocks of the Jurassic, and 10 rocks of the Cretaceous period. Figure 2 shows the relationship between measured velocities and geologic age. Here we have attempted to make as accurate a designation of the age of individual specimens as possible. Values placed at the bottom of the Triassic area are those of Lower Triassic rocks, with the dots in the center, and at the top of the area those for velocity values observed in Middle Triassic and Upper Triassic specimens, respectively.

As will be seen, most velocity values are in the 5000-6500 m/s range. This is so for Triassic, as well as for Jurassic and Cretaceous specimens. Note that the dots are distributed seemingly at random, suggesting, on the basis of the plot in the figure, that velocities apparently are independent of geologic age. This

contradicts experience, and it may be that up to this point the velocity could be determined only in limestones of roughly the same evolution. Therefore, further measurements are needed in additional samples representing broader geohistoric and petrographic ranges in order to determine the general correlation.

Density values are distributed evenly between 2.6 g/cm^3 and 2.9 g/cm^3, as will be seen from Figure 3. The velocity scatter is greater for low density values than for high density values. Based on velocity scatter, the deviation of the correlation curve from the straight line development is greater in the case of the low density values than it is in the 2.7 - 2.9 g/cm^3 range, where it is in good concordance with the straight line. Thus, in the first approximation, velocity increases with density. The looseness of the relationship is shown numerically by the values r = 0.31, r^2 = 9.7%, s = ± 489.3, contained in the figure, and is demonstrated visually by the regression lines.

As the calculations suggest, there is a positive correlation between velocity and density, albeit a slight one. This proves that other material characteristics change with increase in density and this in turn has an effect on the elastic properties of rocks because velocity is inversely proportional to the square root of the density.

The gravimetric density varies between 2.44 g/cm^3 and 2.82 g/cm^3 (Figure 4). The situation is practically identical with the preceding so far as the velocity and gravimetric density correlation is concerned. The correlation coefficient is somewhat larger, 0.34, hence the angle made by the regression lines is smaller than in case of the velocity and density correlation. This shows that velocity depends more on gravimetric density than on density, which too is natural, because in reality matter occurs with its own gravimetric density, so that the velocity is for rocks in this condition, whereas density is a value determined in the laboratory.

Gravimetric density and porosity are inversely related to each other. This /98 will be seen in Figure 5, which shows the correlation between velocity and porosity. Only the correlation curve was plotted, and based on that plot it can be supposed that the regression of the velocity/porosity relationship is non-linear. For this reason the regression lines were not calculated and the value of the correlation coefficient is 0 for the above-mentioned reasons.

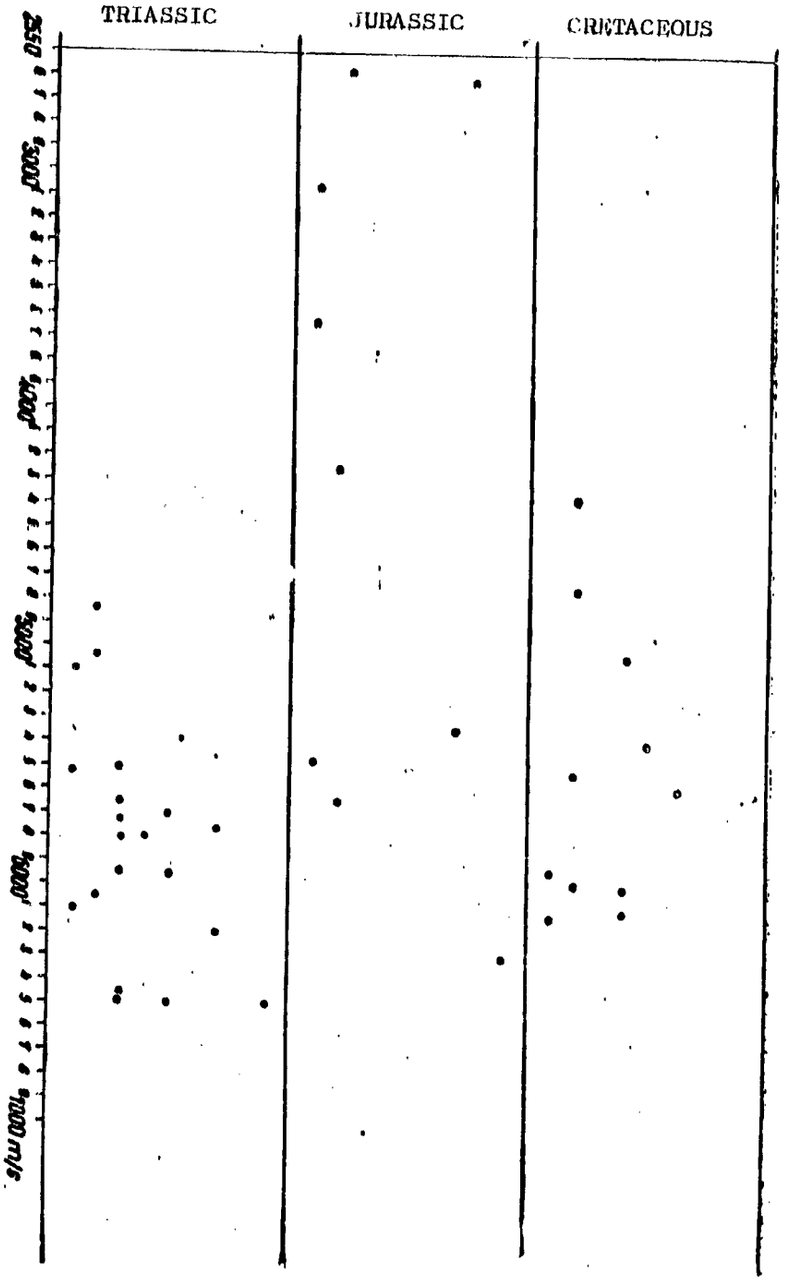

Figure 2. Velocity/geologic age.

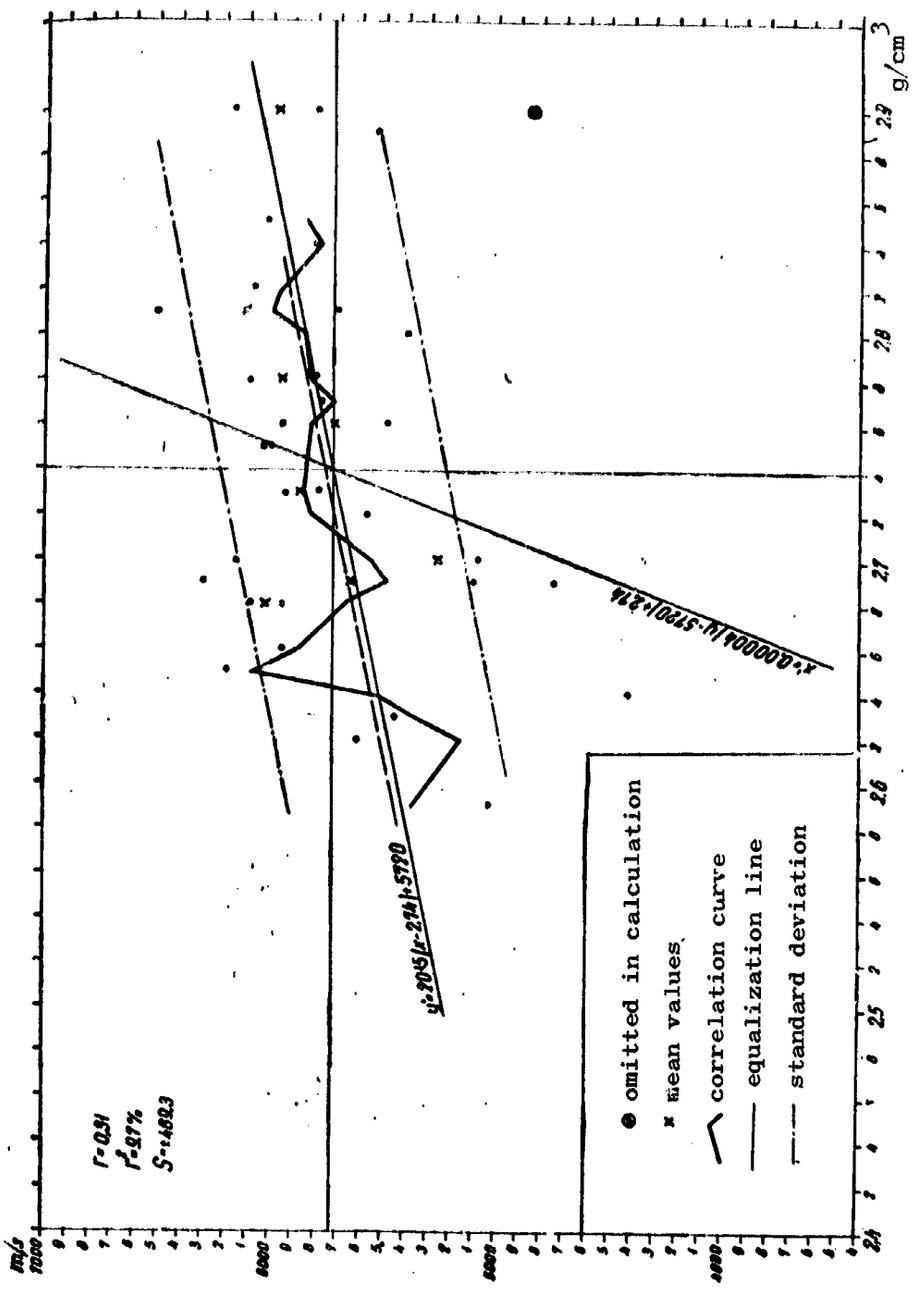

Figure 3. Velocity/density.

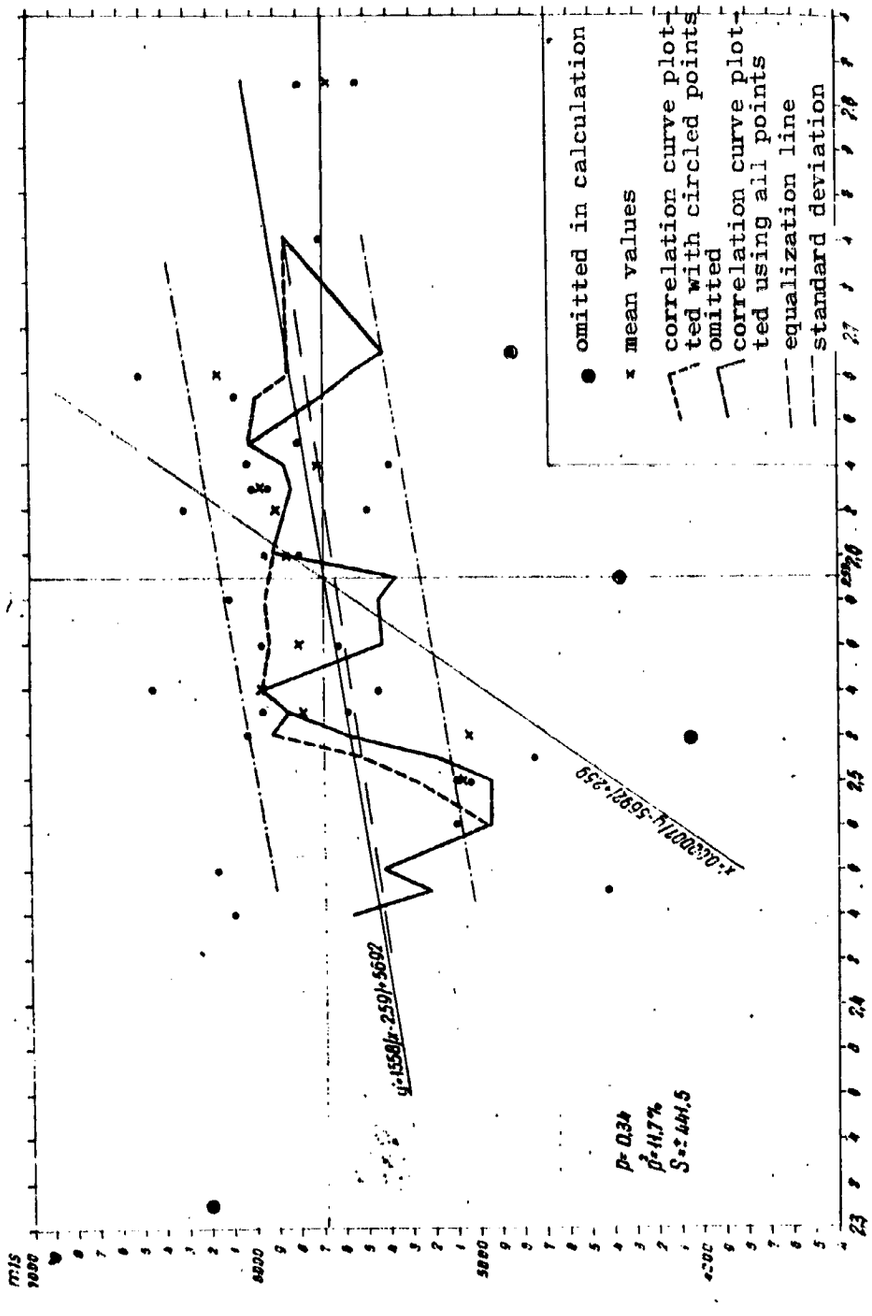

Figure 4. Velocity/gravimetric density.

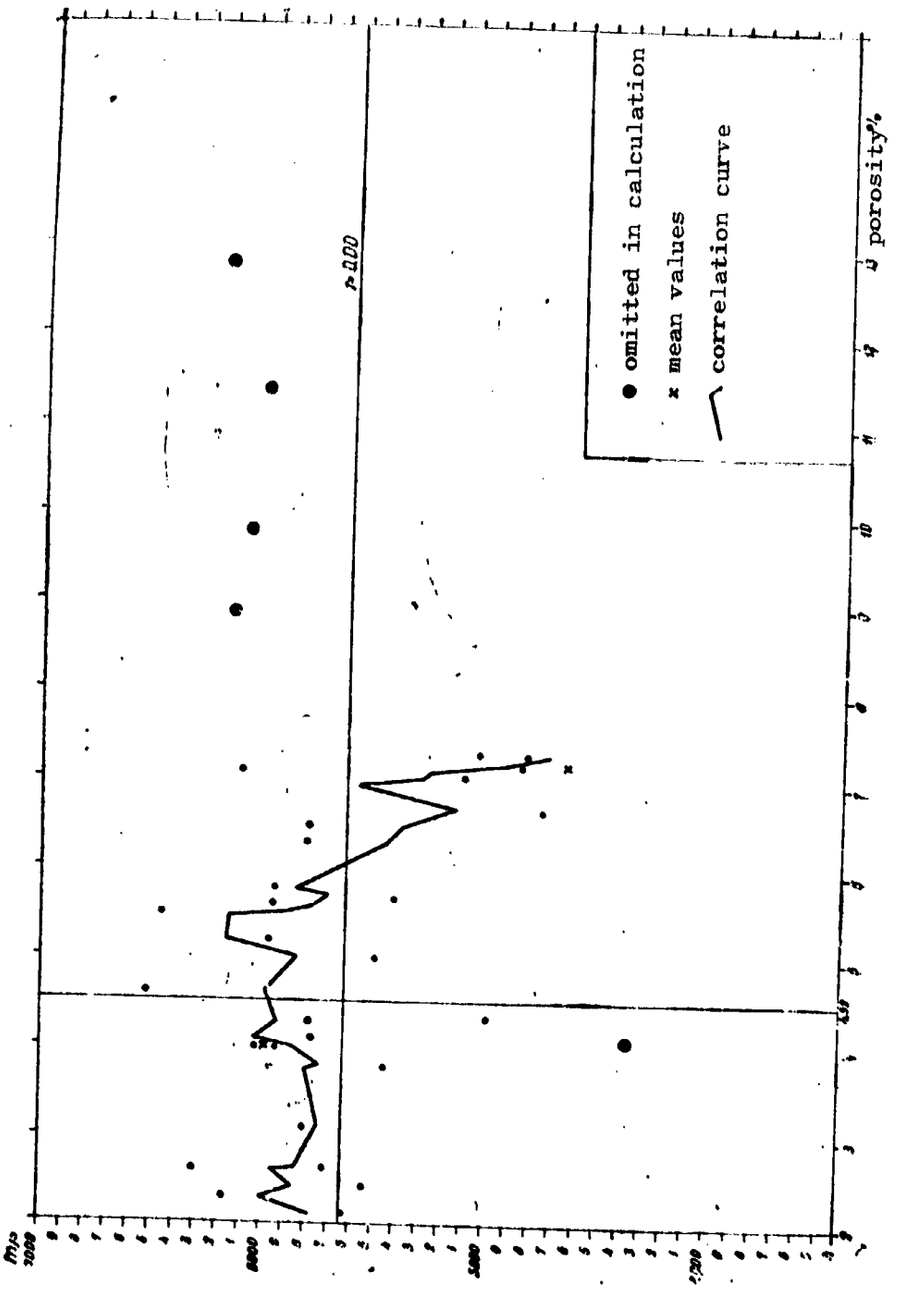

Figure 5. Velocity/porosity.

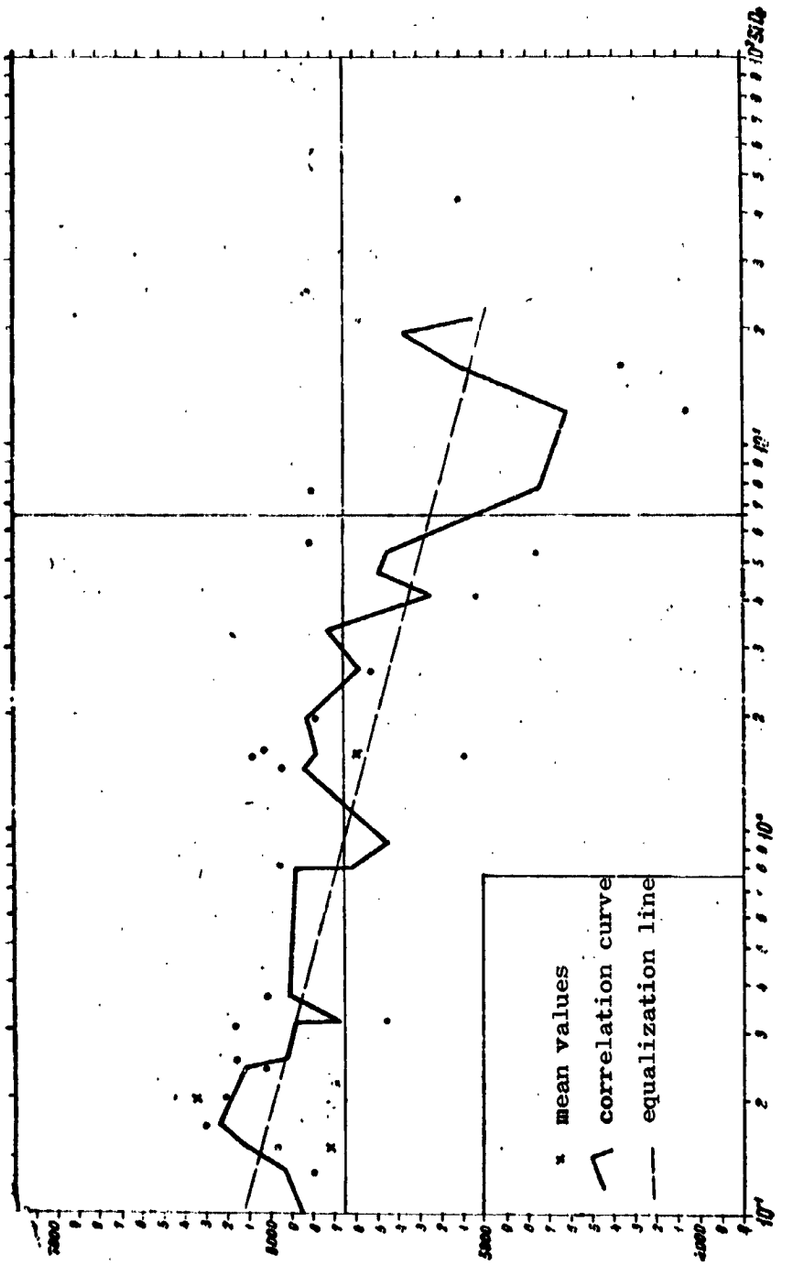

Figure 6. Velocity/SiO_2%.

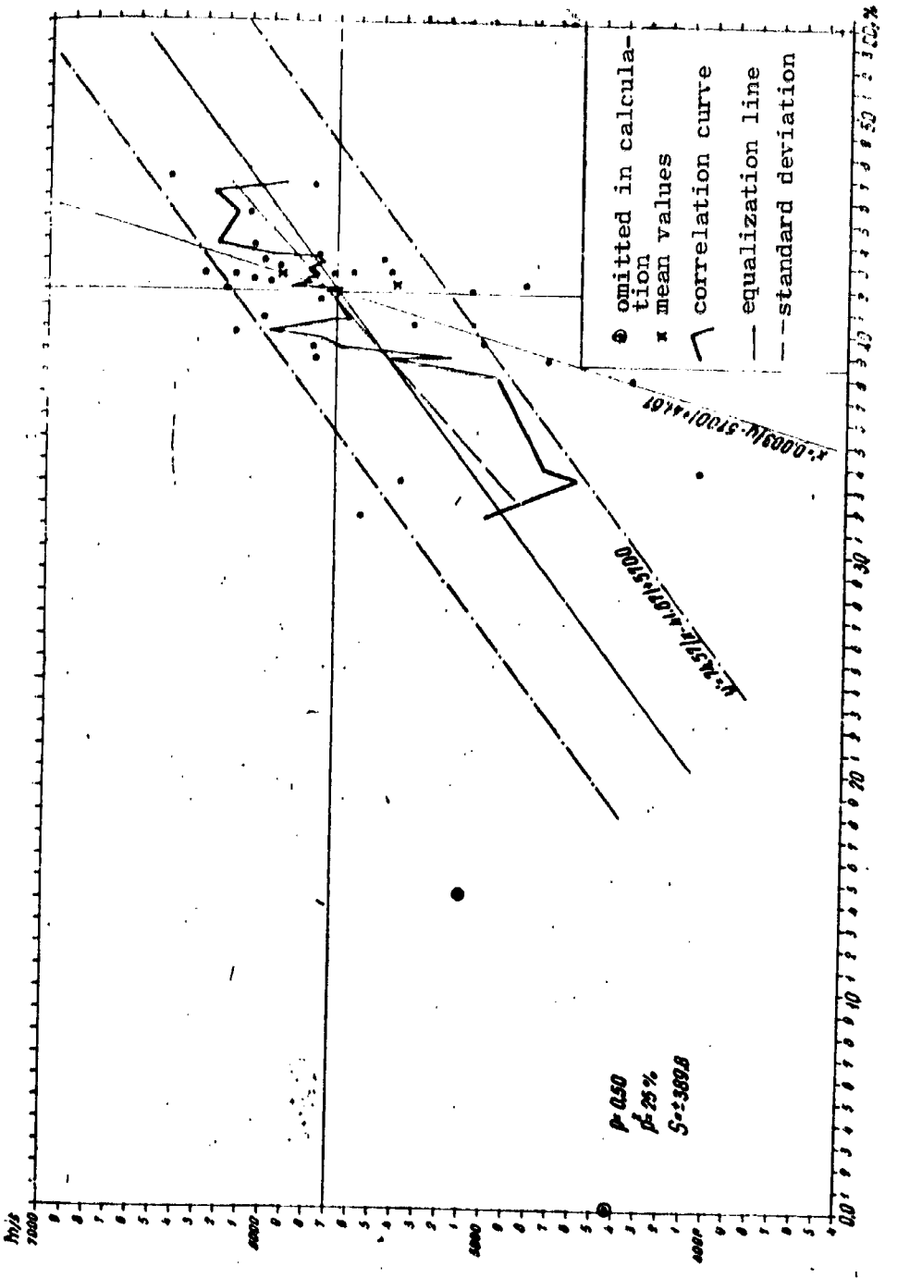

Figure 7. Velocity/CO_2%.

The specimens examined were carbonate sedimentary rocks for the most part. /98
The SiO_2 content demonstrated chemically is probably of colloidal dispersion because of the pelagic facies of the rocks. We also examined the correlation between velocity and SiO_2 content (Figure 6). The SiO_2 content was under 2% in the majority of the specimens. The number of plots with a larger silicic acid content is too small for an evaluation. We therefore made the plots using a semi-logarithmic coordinate system. Since the distribution is uneven, the statistical indices are not characteristic. We therefore plotted only that correlation curve that unequivocally shows the correlation tendency.

The carbonate content, expressed in CO_2, in the specimens is characteristic of the chemical purity of limestones, dolomites. Investigating the correlation between velocity and carbonate content (Figure 7), we see that velocity increases with increase in CO_2 content. Therefore, velocity also is a function of the chemical purity of rocks. It is interesting that among the correlations studied the nexus is the closest between velocity and CO_2 content, as is proved by the data contained in Figure 7.

We compared the in-situ propagation velocities determined by refraction field seismometry with laboratory measurements of velocities in specimens obtained from the appropriate area (Table 3).

But the comparison is only an outline because the origin of the specimens is /99
not exactly identical with the measurement site. The gaps in the table indicate where it would be necessary to make additional refraction measurements and laboratory determinations of velocities in rocks in order to obtain complete knowledge of the country.

Comparing the velocity data obtained in the field with those obtained in the laboratory, it is noteworthy that laboratory investigations generally yielded values larger by 800 to 1000 m/s than did field measurements. This is the more striking because all specimens were of the surface variety whereas refraction velocities indicate velocity in the total rock, which is at depth, under pressure. We are not yet sure of the cause of the discrepancy, but several causes can be suggested. One is that small specimens are more compact, more homogenous, than in-situ rocks. Only pieces of fresh rock were collected. Or it is possible that when long waves are used in refraction measurements the material behaves differently

TABLE 3. FIELD AND LABORATORY PROPAGATION VELOCITY MEASUREMENTS /98

	Age	Central Mountain Range	Banony Mountain	Mecsek Mountain	Matra-Bukk Mountain	Villany Mountain
field	Upper	4500	4400-4500			
laboratory	Cretaceous	5400-5600				
field	Lower					
laboratory			4370-4750			6000-6300
field	Upper					
laboratory						6300
field	Middle-Jurassic	3700-4800				
laboratory		5100-6100				
field	Middle			2900-3200		
laboratory	Lower			3080-4200		
field	Lower			2900-4600		
laboratory				3640-5640		
field	Upper	5300-5900	5000			
laboratory		6100-6500	4480-6500		5800-5960	
field	Middle-Triassic			5200-5800		
laboratory			5380-6560		5800-	5600
field	Lower				4200-5600	
laboratory			4850-6100		6000	

than when oscillations have short periods. If this is so the method distorts the /99 results, and the coefficient of harmonic distortion must be determined by further experimentation. Finally, the cause of the discrepancy can also be that the velocities listed in the table for rock groups of individual ages are related to a rock group of given age, rather than to a single rock. Our laboratory measurements established the velocity in a specimen derived from single components of layer groups that do not necessarily coincide with the refracting layer.

Finally, let us compare our findings with some of the data in the literature on the subject. L. Peselnick and I. Zietz made measurements using three compact, homogenous, fine-grained limestones. The density of their No. 1 specimen was 2.72 g/cm^3, porosity 0.01% (grain size in the base material 18 microns), and the rate of propagation of longitudinal waves was 6100 m/s. Their No. 2 specimen had a density of 2.59 g/cm^3, a porosity of 2.86% (grain size 9 microns), and the measured velocity was 5600 m/s. Finally, their No. 3 specimen had a density of

2.71 g/cm^3 a porosity of 0.0%, and a rate of propagation of 6300 m/s. The above findings are in good concordance with ours, although the methods employed by these authors were considerably different than ours.

C. W. Oliphant has also made velocity determinations of rocks in drill cores. He also studied the effect of moisture, pressure, and temperature on velocity values. He made the measurements in thin rods, taking care that in the measurement of the velocity of longitudinal waves the length of the specimen was considerably greater than its diameter. He field tested the limestones from which the specimens originated in order to have directly comparable laboratory and field values. The field measurements made in Neva limestone of the Upper Carboniferous period showed a velocity of 4470 to 4770 m/s. On the basis of the laboratory measurements made with the specimens, this layer can be divided into more or less clayey levels. These levels yield velocities between 4150-4770 and 6060-6720 m/s. Oliphant corrected the velocity values for water content, pressure, and temperature. As will be seen from the findings, the limestone velocities Oliphant obtained in the laboratory are close to the values we obtained. But his results differ from ours in that his velocity interval, determined by field measurements, coincides with the velocity range established in the laboratory.

The paper by Kuiper, Van Ryen and Koefoed contains measurements made of /100
longitudinal and transverse velocities in 12-30 cm long, and 13 mm thick pure limestone rock specimens in order to establish the Poisson constant. They compared their results for specimen density and porosity, and found that velocity increases with increase in density. The scatter of the velocity values is relatively slight, and they explain this as resulting from the selective purity of the specimens. The limestone velocities they obtained are lower than ours, but specimen density too is less. The velocities in specimens with a density between 1.82 and 2.65 g/cm^3 vary between 2850 and 5370 m/s. Thus, the discrepancy is simply one of degree because the specimens we studied were denser and this can explain the high velocities observed. The correlation between velocity and porosity was not so unequivocal as was the correlation between velocity and density, according to their research.

A further task would be to find answers to the questions that arose during measurements made in the past, and to examine the characteristics of rock

elasticity using other methods. Detailed examination can provide answers to many interesting questions, as well as better reliability of results.

REFERENCES

1. Oliphant, C. W., "Comparison of Field and Laboratory Measurements of Seismic Velocities in Sedimentary Rock", Bull. Geol. Soc. Am., Vol. 61, 1950.

2. Faust, L. Y., "Seismic Velocity as a function of depth and Geologic Time", Geophysics, No. 2, Vol. 16, 1951.

3. Posgay, K., Report on velocities measured in rock specimens in 1955, in the Hungarian State Geophysical Institute.

4. Szomorády Pál, "Determination of the Velocity of Propagation of Elastic Vibrations by the Standing-Wave Method", Annales, Universitatis Scientiarum Budapestionsis de Rolando Eotvos nominatae, 1957, Vol. 1.

5. Poselnick, L., Zietz, I., "Internal Friction of Fine Grained Limestones", Geophysics, April 1959.

6. Kuiper, J., Van Ryen, W. M. L., Koefoed, O., "Laboratory Determination of Elastic Properties of Some Limestones", Geophysical Prospecting, Vol. VII, No. I, March 1959.

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